

# Extrapolating SMBH correlations down the mass scale: the case for IMBHs in globular clusters

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## Abstract

Empirical evidence for both stellar mass black holes ( $M_\bullet < 10^2 M_\odot$ ) and supermassive black holes (SMBHs,  $M_\bullet > 10^5 M_\odot$ ) is well established. Moreover, every galaxy with a bulge appears to host a SMBH, whose mass is correlated with the bulge mass, and even more strongly with the central stellar velocity dispersion  $\sigma_c$ , the  $M_\bullet - \sigma$  relation. On the other hand, evidence for "intermediate-mass" black holes (IMBHs, with masses in the range  $100 - 10^5 M_\odot$ ) is relatively sparse, with only a few mass measurements reported in globular clusters (GCs), dwarf galaxies and low-mass AGNs. We explore the question of whether globular clusters extend the  $M_\bullet - \sigma$  relationship for galaxies to lower black hole masses and find that available data for globular clusters are consistent with the extrapolation of this relationship. We use this extrapolated  $M_\bullet - \sigma$  relationship to predict the putative black hole masses of those globular clusters where existence of central IMBH was proposed. We discuss how globular clusters can be used as a constraint on theories making specific predictions for the low-mass end of the  $M_\bullet - \sigma$  relation.

**Keywords** Black holes; Globular clusters

## 1 Introduction

The empirical evidence for the ubiquity of both stellar mass black holes (black hole mass  $M_\bullet$  of  $\sim 1 - 15 M_\odot$ ) and supermassive black holes (SMBHs,  $M_\bullet > 10^5 M_\odot$ )

is well established. While it is estimated that there are about  $10^7 - 10^9$  stellar-mass black holes in every galaxy (e.g., Shapiro & Teukolsky 1983; Brown & Bethe 1994), every galactic bulge appears to host a SMBH. Moreover, the kinematically determined mass of these SMBHs is correlated with the mass of the bulge, and even more strongly with the central stellar velocity dispersion  $\sigma$ , the  $M_\bullet - \sigma$  relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy & Gebhardt 2001; Tremaine et al. 2002). Active galactic nuclei (AGN), which have long been believed to be driven by accretion around SMBHs and whose SMBH masses have been estimated from reverberation-mapping, are also consistent with the  $M_\bullet - \sigma$  relationship (e.g., Wandel 2002; Bentz et al. 2009, and references therein). The corollary is that the nuclear activity is a phase (or more) in the life of (at least) every galaxy with a bulge.

The  $M_\bullet - \sigma$  relation has been extended down to black hole masses of  $\sim 10^5 M_\odot$  (Barth et al. 2005; Greene & Ho 2006) by searching for central BHs within very low-luminosity AGN. Their dynamical studies are an unambiguous verdict on the presence of central BHs in dwarf ellipticals and very late-type spirals (e.g., NGC4395 by Greene & Ho (2007) and references therein). Even lower mass black holes have been inferred from non-dynamical methods for other low-luminosity AGN (e.g., Dong et al. 2007). In spite of considerable efforts, however, evidence for black holes of still lower mass, *viz.*, the intermediate-mass black holes (IMBHs, of masses  $10^2 - 10^4 M_\odot$ ), is relatively sparse. Attempts to discover IMBHs in globular clusters via their X-ray emission have been on for a long time, (e.g., Bahcall & Ostriker 1975), and although the recently discovered ultra-luminous X-ray sources (ULXs) have been attributed to IMBHs (e.g., Colbert & Mushotzky 1999), this suggestion has also been contested (e.g., Berghea et al. 2008).

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Extrapolating the  $M_\bullet - \sigma$  correlation down the mass scale predicts that IMBHs can be found in stellar systems that have velocity dispersions of  $< 30$  km/sec, clearly pointing to the globular clusters. Observational evidence for such black holes are only a handful, however (*cf.* references in Table 1). Furthermore, theoretical results on IMBHs in globular clusters remain ambiguous, at best. Some theories predict the necessity of most (if not all) Galactic globular clusters to host central black holes (e.g., Miller & Hamilton 2002), while some argue for the impossibility of globular clusters to form and/or retain black holes in their cores (e.g., Favata et al. 2004; Kawakatu & Umemura 2005). The importance of investigating the possibility of globular clusters hosting IMBHs cannot be overestimated. While a central IMBH would clearly impact the evolution of the globular cluster itself, more generally, IMBHs are crucial to link the formation processeses of stellar-mass BHs and SMBHs, and could have served as seeds for the growth of SMBHs. Extending the local BH mass function to the extreme low end can help in understanding whether there is a minimum galaxy mass or velocity dispersion below which BHs are unable to form or grow (e.g., Bromley et al. 2004). Globular clusters and galactic bulges are both ‘hot’ stellar systems, and, since all large bulge systems seem to have a central black hole, to the extent that a massive, bound globular cluster can be viewed as a “mini-bulge”, it may be that every dense stellar system (small or large) hosts a central black hole (Gebhardt et al. 2002). BHs at the low end of the mass ladder can be used as a constraint on theoretical models with different predictions on the  $M_\bullet - \sigma$  behaviour. For example, the prediction that  $M_\bullet - \sigma$  relation shall substantially steepen below  $\sigma = 150$  km/sec (Granato et al. 2004) is not supported by the low-mass AGN sample (Barth et al. 2005). The question of IMBHs also has bearing on debates in cosmology, since the cosmic mass-density of IMBHs could exceed that of SMBHs ( $\Omega \approx 10^{-5.7}$ ), and may even account for all the baryonic dark matter in the universe, with  $\Omega \approx 10^{-1.7}$  (van der Marel 2003).

The few recent reports on the detection of central black holes in some globular clusters seem to suggest that globular clusters do follow the  $M_\bullet - \sigma$  relation for SMBHs (van der Marel et al. 2002; McLaughlin et al. 2006; Noyola et al. 2008; Lanzoni et al. 2007; Gebhardt et al. 2002) and that these BHs represent the ‘true’ IMBHs in the mass range of  $10^2 - 10^4 M_\odot$ . In this paper, we compile published discoveries of central black holes in globular clusters and investigate the consistency of the data with the  $M_\bullet - \sigma$  and  $M_\bullet$ -luminosity relations. Using these globular clusters as a constraint on the slope of the extended  $M_\bullet - \sigma$  relation, we estimate the black hole masses for a sample of globular

clusters that are proposed to host IMBHs and discuss the implications.

## 2 $M_\bullet - \sigma$ Correlation

Although the  $M_\bullet - \sigma$  relationship for galaxies is very well established, the published estimates for the slope parameter  $\beta$  of the relationship span a wide range (3.68 to 4.86), the reasons for this discrepancy discussed by Tremaine et al. (2002) and Ferrarese & Ford (2005). As a rough estimate from this correlation, for a typical globular cluster with central dispersion  $\sigma_c$  of the order 10 km/sec, the mass of the central black hole would be  $M_\bullet \sim 10^3 M_\odot$ . This roughly coincides with the estimate from the Maggarian relation  $M_\bullet \sim 10^{-3 \pm 1} M$  (Magorrian et al. 1998), and with the theoretical estimates of the formation of the central BH from the initial  $\sim 50M_\odot$  seed by stellar/low-mass objects accretion (Miller & Hamilton 2002),  $M_\bullet = 10^3 M_\odot \times 10^{-(M_V+10)/2.5}$ .

### 2.1 Constraints on the $M_\bullet - \sigma$ relation by globular clusters candidates

For investigation of the very low-end extrapolation of the  $M_\bullet - \sigma$  relation, we take the globular clusters where the presence of the central black hole was inferred from optical observations of either individual stars or by using integrated light techniques. The data on the clusters are given in Table 1.

In Figure 1 we plot the black hole masses and central velocity dispersions for globular clusters (Table 1), together with the sample of galaxies with secure BH mass estimates available to date. The galaxy data consist mainly of a sample of 49 galaxies (Gültekin et al. 2009) with directly dynamically-measured black hole masses (called GRG sample hereafter). The galaxies included in their sample are only elliptical or with classical bulges or pseudobulges, and since a globular cluster can be viewed as a ‘mini-bulge’, we favour this sample. To the GRG sample we have added six galaxies from Hu (2008); the reason for their absence in GRG sample is unclear, since their mass measurements are also dynamical, and the galaxies are either elliptical or having pseudobulges. We have also added the latest estimates of the black hole mass in NGC 4395 (Peterson et al. 2005) and Pox 52, the lowest-mass AGN to date (Barth et al. 2004). Though mass estimates for these two black holes are not from gas or stellar dynamics (the reason why AGN, for example, were excluded from GRG sample), these measurements were made by

**Table 1** Globular clusters with the reported central black holes

Cluster Name	Other Name	$M_{\bullet}$ ( $10^3 M_{\odot}$ )	$\sigma$ (km/sec)	$M_V$	Ref.
NGC 104	47Tuc	$1.0^{+0.5}_{-0.5}$	$11.6 \pm 0.8$	-9.42	1
NGC 5139*	$\omega$ Cen	$40.0^{+7.5}_{-10.0}$	$23.0 \pm 2.0$	-10.29	2
NGC6388†		$5.7^{+5.7}_{-2.85}$	$18.9 \pm 3.6$	-9.42	3
NGC 7078‡	M15	$2.5^{+0.7}_{-0.8}$	$14.1 \pm 3.2$	-9.17	4,5,6
G1 (M31)	Mayal II	$18.0^{+5.0}_{-5.0}$	$25.1 \pm 1.7$	-10.94	7

*Key to columns:* (1)-(2) cluster identification number and name, (3) BH mass  $M_{\bullet}$  with error bars (where reported), (4) central velocity dispersion, (5) V-band absolute magnitude, (6) references are the BH measurement papers: (1) McLaughlin et al. (2006); (2) Noyola et al. (2008); (3) Lanzoni et al. (2007); (4) van der Marel et al. (2002); (5) Gerssen et al. (2002); (6) Gerssen et al. (2003); (7) Gebhardt et al. (2005).

\* this value has recently been reduced to the upper limit of  $1.2 \times 10^4 M_{\odot}$  (Anderson & van der Marel 2009), see discussion in Sec. 2.2.

† a factor of two uncertainty has been assigned to this BH mass.

‡ the reported masses for this cluster range from 1 to  $9 \times 10^3 M_{\odot}$ ; the listed mass is the most probable value, see latest (Kiselev et al. 2008).

multiple methods and are considered to be quite reliable. The data for these additional galaxies are given in Table 5 in Appendix B.

We assume that there is an underlying relation of the form

$$y = \alpha + \beta x, \quad (1)$$

where  $y = \log(M_{\bullet}/M_{\odot})$ ,  $x = \log(\sigma_e/\sigma_0)$ ;  $\sigma_0$  is some reference value usually chosen to be 200 km/sec (it was noticed by Tremaine et al. (2002) that this choice reduces the uncertainties in the intercept  $\alpha$ ), and  $\sigma_e$  is the effective velocity dispersion, defined in Gürtekin et al. (2009) as the spatially averaged, rms, line-of-sight stellar velocity within the effective radius  $r_e$ . It was noticed by Merritt & Ferrarese (2001) that  $\sigma_e$  might be expected to reflect the depth of the stellar potential well more accurately than the central velocity dispersion,  $\sigma_c$ . However, when this was not available, we have used  $\sigma_c$  as, on average, there is remarkably little difference between  $\sigma_e$  and  $\sigma_c$  (Merritt & Ferrarese 2001; Gürtekin et al. 2009). Many of the galaxies in the sample have assymetric quoted errors, but for simplicity we assume here that the measurement errors are symmetric in both parameters with root-mean-square (rms) values  $\epsilon_{xi}$  and  $\epsilon_{yi}$  for galaxy (or cluster)  $i$ . In our sample we used the published bounds to the  $1\sigma$  range in BH mass, and upper and lower limits to the disper-

sion<sup>1</sup>. The goal is to estimate the best-fit values of  $\alpha$  and  $\beta$  and their associated uncertainties for the total sample of galaxies and five globular clusters (using the symmetric least-squares method).

Figure 1 shows the correlation between  $M_{\bullet}$  and the velocity dispersion of the host. The best-fit linear relation for the sample with only galaxies (designated “Sub-sample”) is

$$\log\left(\frac{M_{\bullet}}{M_{\odot}}\right) = (8.17 \pm 0.06) + (4.16 \pm 0.3) \log\left(\frac{\sigma_e}{\sigma_0}\right), \quad (2)$$

and the slope of the relation changes only slightly with inclusion of the five globular clusters (“Full sample”)

$$\log\left(\frac{M_{\bullet}}{M_{\odot}}\right) = (8.19 \pm 0.06) + (4.20 \pm 0.2) \log\left(\frac{\sigma_e}{\sigma_0}\right). \quad (3)$$

These data are summarised and compared with the best results from Gürtekin et al. (2009) in Table 2.

<sup>1</sup>Errors in  $x$  and  $y$  are assumed to be  $(\log \sigma_{\text{upper}} - \log \sigma_{\text{low}})/2$  and  $(\log M_{\bullet,\text{high}} - \log M_{\bullet,\text{low}})/2$ , respectively. The measurement errors in mass are added together with the intrinsic scatter,  $\epsilon_0 = 0.4$ , in quadrature, using the best estimate of  $\epsilon_0$  from GRG sample.

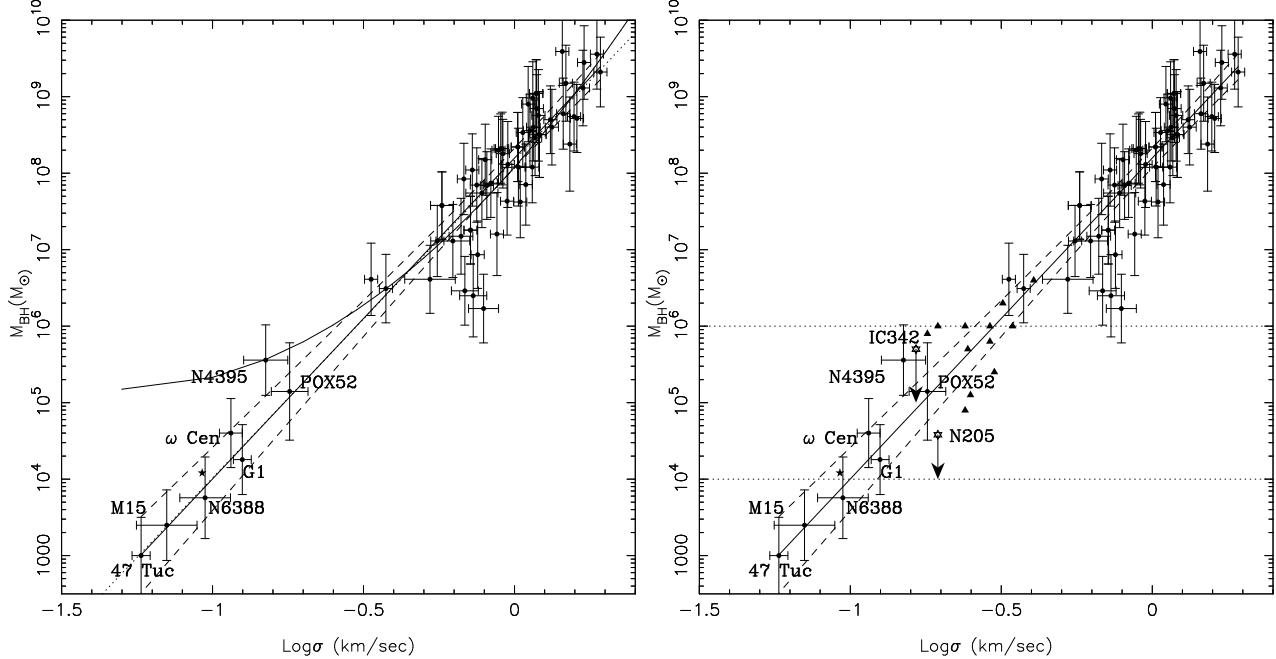


Fig. 1.— Mass of the central black hole  $M_{\bullet}$  (in solar masses) vs. velocity dispersion  $\sigma$  ( $= \sigma_e/200$ ) km/sec for galaxies and globular clusters. Dotted line is the linear regression fit for only galaxies and solid line is the fit including the globular clusters. Dashed line is the 2-sigma error on the regression. Solid curved line is the quadratic fit for GRG sample (see in the text). Single star is the most recent estimate of the  $\omega$  Cen black hole mass (Anderson & van der Marel 2009). *Right:* Clearly seen the division of the plot into three distinct regions, upper part is occupied by SMBHs, middle by MBHs with inclusion of N205 and IC342 upper limits, bottom by IMBHs. Filled triangles are the sample of low-mass AGNs of Greene & Ho (2006). See discussion in Sec. 2.2.

The fact that globular clusters fit the  $M_{\bullet} - \sigma$  relation is remarkable, and rather puzzling, considering that the formation mechanisms for the central black holes are believed to be different: the SMBHs in galaxies are hypothesized to have formed through gas collapse and subsequent gas accretion, while the central black holes in globular clusters are believed to have formed through either collapse of a stellar cluster (e.g., Portegies Zwart & McMillan 2002) or through stellar (or low-mass remnants) accretion onto an existing relatively massive black hole (Miller & Hamilton 2002). However, both theories agree that there may have been an initial seed, an IMBH of order  $\sim 10^3 M_{\odot}$  for the case of galaxies, and a  $\sim 50 M_{\odot}$  black hole for the case of globular clusters. The fact that all proposed BHs in globular clusters fit the  $M_{\bullet} - \sigma$  correlation suggests that there must be some previously unrecognized connection between the formation and evolution of globular clusters, galaxies and their central black holes.

## 2.2 SMBHs to IMBHs through massive black holes

Apart from the remarkably consistent extrapolation of the  $M_{\bullet} - \sigma$  relation down to the very low end, the

right panel in Figure 1 displays three distinct regions. The top right corner is populated by a well-known and well-established sample of a SMBHs, which has a relatively sharply defined low edge. It was proposed long ago that there might be a physically determined lower limit [ $> 10^6 M_{\odot}$ ] to the mass of a SMBH (Haehnelt et al. 1998), and recently Wehner & Harris (2006) argued that formation of a black hole is strongly favoured above this limit. It was the need to determine the low end of the SMBH mass function that started the active IMBH search. Elucidating the demographics of low-mass BHs can provide the critical input to test the theoretical models of quasar formation (Haehnelt et al. 1998). In particular, the low-mass cut-off in the BH mass function today provides a constraint on the mass function of seed BHs. Models of different seed masses predict different BH occupation fractions at the low end of the mass ladder, ranging from some galaxies hosting tiny ( $< 10^4 M_{\bullet}$ ) BHs to virtually no central black holes below 60 km/sec (see discussion in Sect. 4.2).

Dynamical studies present an unambiguous verdict on the existence of central black holes in dwarf stellar systems, and these BHs can be properly named massive black holes — MBHs — as opposed to their

**Table 2**

Sample	$\alpha$	$\beta$	$\chi^2$	$\chi^2/\text{dof}$
Subsample	$8.17 \pm 0.06$	$4.16 \pm 0.3$	50.9	0.85
Full sample	$8.19 \pm 0.06$	$4.20 \pm 0.2$	50.9	0.78
GRG (TO2ind) <sup>†</sup>	$8.19 \pm 0.06$	$4.06 \pm 0.37$	...	...
GRG best <sup>‡</sup>	$8.12 \pm 0.08$	$4.24 \pm 0.41$	...	...

<sup>†</sup> Method of Tremaine et al. (2002) applied to a GRG sample without the upper limits (Gültekin et al. 2009). The intrinsic scatter is added in quadrature to the measurements errors in the expression for  $\chi^2$ .

<sup>‡</sup> The best fit in Gültekin et al. (2009).

higher-mass counterparts, with a range in masses of  $\sim 10^4 - 10^6 M_\odot$  and velocity dispersions of  $\sim 25 - 65$  km/sec. This region is flanked from the top by a few massive/supermassive galaxies such as, for example, M32, Milky Way and Circinus with the lowest mass in SMBH region of  $1.7 \times 10^6 M_\odot$ . It is populated by well-established dwarfs, such as NGC 4395 and POX52 (see Table 5). The upper limits for black holes in the galaxies IC342 and NGC 205 ( $1.5 \times 10^4 M_\odot$  from Boeker et al. (1999) and  $2.2 \times 10^4 M_\odot$  from Valluri et al. (2005), respectively) lie in this region as well. However, current dynamical techniques do not have the spatial resolution needed to resolve the gravitational sphere of influence of a low-mass ( $\sim 10^5 M_\odot$ ) BH outside of the Local Group, while even local studies can only place upper limits (e.g. NGC 205), or reject the existence of a BH altogether (M33). Therefore, the search is forced to use AGN activity as a signature for the BH. The recently discovered SDSS DR4 sample of dwarf Seyfert 1 nuclei galaxies, referred to herein as the sample of Greene & Ho (2006), may represent an upper envelope of the population of MBHs — black holes in low-mass galaxies. This sample has a median mass of  $\langle M_\bullet \rangle = 1.3 \times 10^6 M_\odot$  (Greene & Ho 2006) with the lowest BH mass of  $8 \times 10^4 M_\odot$ , and the host galaxies do belong to the low-mass (low-luminosity) population. The broad-line AGN SDSS DR4 sample with mass range of  $5 \times 10^4 - 10^6 M_\odot$  (Dong et al. 2007) brings the present census of these AGN MBHs up to 400. However, since the majority of this MBH population are AGNs, being quite compatible with the low-end extension of active SMBHs in their properties, the question still remains as to whether normal dwarfs also have central BHs. Furthermore, globular clusters G1 and  $\omega$  Cen, that lie at the lower end of the MBH region, are now believed to be not genuine globular clusters, but the cores of the accreted galaxies stripped by tidal forces (Mackey & van den Bergh 2005, and refs therein). As such, the central black holes of G1 and  $\omega$  Cen are still *galactic* black

holes, and their masses of  $\sim$  few  $\times 10^4 M_\odot$  thus represent the lowest limit for the massive *galactic* black holes. Incidentally, the ratio of  $M_\bullet$  to the total mass of  $\omega$  Cen is much higher than the “canonical” value of  $\sim 0.3\%$ , but if  $\omega$  Cen is the core of an accreted dwarf, most of its mass would have been stripped during the tidal evolution and, once corrected for that, a mass of  $4 \times 10^7 M_\odot$  obtained by modeling (Noyola et al. 2008), puts the observed black hole near the 0.3% value, which suggests that when this galaxy was accreted, it already possessed a central black hole. It should be noted that recently Anderson & van der Marel (2009) reported new, reduced, values for both BH mass and velocity dispersion leave the  $\omega$  Cen black hole on the same  $M_\bullet - \sigma$  relation, and in the same MBH region.

The other, “genuine”, globular clusters, such as M15, 47 Tuc and NGC 6388, represent a third region of the ‘genuine’ IMBH domain, narrowing the mass range of IMBHs to  $\sim 10^2 - 10^4 M_\odot$ .

Thus, the earlier existing gap in the BH ‘mass ladder’ seems to be rapidly filling up; with BHs smoothly populating the whole range from  $1 M_\odot$  up to nearly  $10^{10} M_\odot$ , with a clear distinction of mass ranges between different stellar systems; stellar-mass black holes are loners or in binary systems, IMBHs live in small stellar systems like GCs, and massive black holes (MBH+SMBH) in the cores of galaxies. This brings back the question of dynamical detection of BHs in low-mass non-active stellar systems, with globular clusters being the best potential candidates. Most of the Galactic globular clusters are close by, and while optical observations are still difficult due to the extreme crowding in the centres, it may be possible to discover BHs from radio and X-ray observations and, in the future, from microlensing (Safonova & Stalin 2009) and gravitational waves’s observations.

### 2.3 Black hole mass estimates in a sample of globular clusters

It was found that the  $M_\bullet - \sigma$  relation is a powerful tool as it allows the prediction of BH masses (which are diffi-

cult to measure directly) from readily available galaxy parameters (Lauer et al. 2007); for example, from a single, low-resolution observation of a galaxy’s velocity dispersion, its central BH mass can be estimated with an accuracy of  $\sim 30\%$  or better (Ferrarese & Merritt 2000). Notably, BH masses measured by reverberation-mapping and BH virial mass estimates for some local AGNs are broadly consistent (Gebhardt et al. 2000; Greene & Ho 2006). Based on the remarkable consistency of the BH masses discovered in globular clusters described in the previous section, we applied the  $M_\bullet - \sigma$  relation to estimate the masses of possible central black holes in some Galactic globular clusters. Although the precise nature of this correlation is not yet understood, there may be no limit to the range of velocity dispersions over which the  $M_\bullet - \sigma$  relation can apply (Begelman & Nath 2005). We have applied the results of the Sec. 2.1 (Eq. 3) to estimate the masses of black holes for a sample of globular clusters and presented the results in Table 6. The list of candidate globular clusters grows continuously as different methods of detections are being suggested. Our sample of Galactic GCs that may host a central black hole (Table 6) was compiled on the basis of these different proposals.

Since high-centrally concentrated globular clusters and especially core-collapsed clusters have long been proposed as harbouring central black holes, we have included in our sample all Galactic core-collapsed (or post-core-collapsed) clusters (Trager et al. 1995). However, this view has been challenged recently by Baumgardt et al. (2005) who has argued that, on the contrary, no core-collapsed clusters can harbour central black holes, as they would quickly puff up the core by enhancing the rate of close encounters, tending to prevent the core collapse and leaving an imprint of a shallow cusp; in other words, the clusters with flat large cores and King profiles outside would rather host a central black hole. This view was further reinforced by Miocchi (2007), who in addition suggested looking for the extreme horizontal-branch (EHB) stars as a possible fingerprint of the presence of an IMBH. However, Hurley (2007) issued a cautionary note on using large core radius as an indicator of an IMBH presence, since other factors, such as the presence of a stellar BH-BH binary in the core, can flatten the measured luminosity profile and enlarge the core radius, and that it is still too early to abandon the IMBH indicators used earlier, such as the steepening of a M/L ratio in GC cores (Gebhardt et al. 2005). In our candidate sample (Table 6) we have included candidates from Baumgardt et al. (2005) and Miocchi (2007).

It should be noted that in Table 1 of reported BH cases both variants are included, G1 and  $\omega$  Cen having

large cores and M15 a collapsed core. NGC 6388 is the cluster for which both Miocchi (2007) and Baumgardt et al. (2005) agree on the existence of the central black hole.

Recently Drukier & Bailyn (2003) have suggested that high-velocity stars in GCs cores can be used to reveal the central BHs and have drawn a list of most probable clusters based on existing observations. Based on radio emission as a possible test of the existence of IMBHs in GCs, Maccarone (2004) suggested that the radio, rather than the X-ray, observations can be a more successful test for a central IMBH and have calculated expected radio flux densities for a few possible candidates. One more technique to search for the massive BH-BH binary system in the core of GCs is the use of exotic ejected binary systems, for which the cluster NGC 6752 is a very good candidate, having a binary pulsar system at 3.3 half-mass radii from the core and a high central mass-to-light ratio (Colpi et al. 2003). In Table 6, the last but one column lists the reason for the selection of a cluster. Black hole masses from these different predictions are listed in the last column of the Table.

### 3 $M_\bullet - \text{Luminosity}$ correlation

The black hole mass in galaxies correlates linearly with the absolute luminosity of the bulge of the host galaxy (Kormendy & Richstone 1995; Magorrian et al. 1998). We use here the extinction-corrected, bulge (or total for ellipticals), V-band luminosities calculated from absolute magnitudes, using

$$\log(L_V/L_{\odot,V}) = 0.4(4.83 - M_V), \quad (4)$$

where  $M_V$  for the GRG sample is taken from Gültekin et al. (2009), for additional galaxies from Lauer et al. (2007) (see Table 5), and for globular clusters from the Harris catalog (Harris 1996). By the same fitting method as in Sec. 2.1, with the exception of using measurement errors only on mass (routine ‘fit’ from Press et al. 1992), the linear regression for our sample gives

$$\log\left(\frac{M_\bullet}{M_\odot}\right) = (8.89 \pm 0.08) + (1.03 \pm 0.04) \log\left(\frac{L_V}{10^{11}L_{\odot,V}}\right). \quad (5)$$

Comparison with other fits is given in the Table 3.

Since five reported globular clusters fit this correlation quite well (within the scatter), we may expect that the sample of candidate globular clusters will follow the same. We have plotted the calculated black hole masses for globular clusters from the Table 6, denoted

**Table 3**

Sample	$\alpha$	$\beta$	$\chi^2$	$\chi^2/\text{dof}$
Full sample	$8.89 \pm 0.08$	$1.03 \pm 0.04$	68.7	1.6
Subsample	$9.05 \pm 0.10$	$1.33 \pm 0.11$	62.5	1.52
GRG best <sup>‡</sup>	$8.95 \pm 0.11$	$1.11 \pm 0.18$	...	...
Tremaine sample <sup>†</sup>	$8.41 \pm 0.11$	$1.40 \pm 0.17$	...	...

<sup>†</sup> Symmetric least-squares fit applied to the Tremaine et al. (2002) sample by Lauer et al. (2007).

<sup>‡</sup> The best fit in Güttekin et al. (2009).

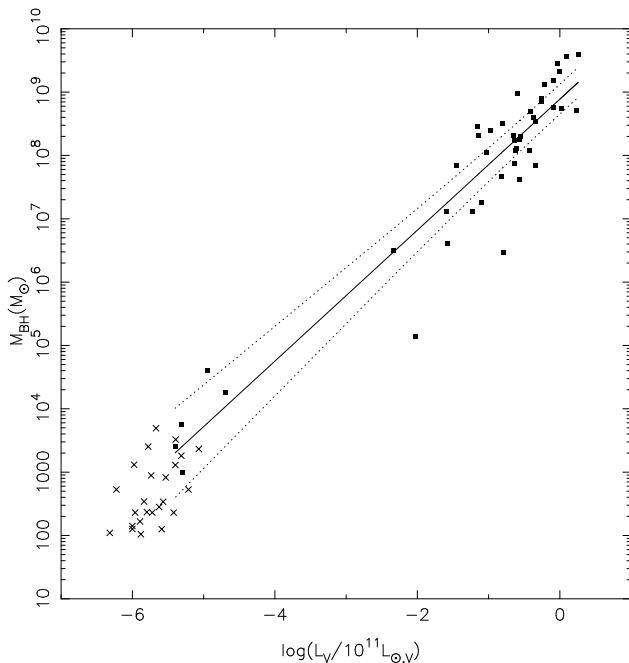


Fig. 2.— Mass of the central black hole  $M_{\bullet}$  (in solar masses) vs. V-band luminosity of the bulge (or cluster) for galaxies and globular clusters. The original full sample is represented by the filled squares. The clusters from Table 6 are represented by crosses. Solid line is the linear regression fit for our full sample. Dashed lines are 3-sigma errors on the regression fit. Clusters with masses inferred from Eq. 3 (crosses) fall on and around the best-fit line.

by crosses, against their V-band luminosities in Fig. 2. It should be noted from Table 6 that black hole masses depend strongly on velocity dispersion, with  $\sigma_c \lesssim 7$  km/sec giving a mass too low to be considered seriously. It is most likely that only the black holes of masses  $\gtrsim 100 M_{\odot}$  would remain at the centres, with the lighter ones ejected from the cluster due to gravitational interactions (e.g., Miller & Hamilton 2002). Thus, for the Fig. 2 we retained only the black holes with masses  $> 100 M_{\odot}$ . The solid line gives the best

fit for our full sample and the dashed lines give the  $3-\sigma$  confidence limits on the fit.

It seems intriguing that the  $M_{\bullet}$ –luminosity relation is preserved even for the putative GC black holes. The larger scatter than for  $M_{\bullet} - \sigma$  relation is also observed, just like for the more massive counterparts. Since the  $M_{\bullet}$  – luminosity relation is considered to be the reflection of  $M_{\bullet}$  – bulge mass relation, and GCs follow different fundamental-plane relations than galaxies with classical bulges (e.g., Wehner & Harris 2006, and the numerous references cited therein), it seems strange that they shall continue on the same relation. At least for the low-mass local AGN sample, Greene et al. (2008) suggested that this relation will look different, with a bias towards more massive host galaxies for a given BH mass. This relation is also suspected to deviate in the regime of the most luminous elliptical galaxies, with black hole masses of more than  $10^9 M_{\odot}$  (Lauer et al. 2007). It was proposed that, at that end, the bulge luminosity is a better predictor for a black hole mass than velocity dispersion, whereas at the low-mass end (globular clusters), the BH growth really depends on a (relatively) local stellar velocity dispersion, as would be expected in a model where the BH accretion is fed by the capture of individual stars (Miralda-Escudé & Kollmeier 2005) and, moreover, the GC mass is susceptible to the tidal erosion. When we applied the weighted least-squares fit (neglecting measurement errors in both variables for simplicity, using routine ‘fit’ from Press et al. (1992)) to the sample of only globular clusters (five clusters from Table 1 plus candidate clusters from Table 5), the slope indeed increased, but not dramatically, only to  $1.355 \pm 0.25$ , approaching the slope for the sample of only galaxies. Similar analysis was done by Miocchi (2007) for the sample of globular clusters, where black hole masses were estimated by constraining the parametric model of a globular cluster with IMBH from observed central surface density profile and concentration parameter. In their sample the black hole mass appears to be poorly correlated with the V-band luminosity of a cluster, however it shall be noted that

black hole masses obtained by that method have huge uncertainties and the sample used to obtain the correlation is quite small. Their  $M_{\bullet} - \sigma$  relation also has a very shallow slope of 1.2. When using the  $M_{\bullet} - \sigma$  relation for the globular cluster sample, though, it should be borne in mind that the reported velocity dispersion measurements for most of our candidate clusters may not be representative of the (higher) actual values in the inner (unresolved) regions of the clusters. Observations of globular clusters with higher spatial resolution may provide better constraint on this low-end mass-ladder extension. The latest example of under-estimation of the central velocity dispersion is the report by Ibata et al. (2009), in which the globular cluster M54 (NGC 6715) is found to host a  $\sim 10^4 M_{\odot}$  black hole; the previous central velocity dispersion from, for example, Pryor & Meylan (1993) was  $\sigma = 14.2$  km/sec, but Ibata et al. (2009) report a value of  $\sigma = 20.2$  km/sec.

## 4 Discussion

### 4.1 Central BHs and evolution of globular clusters

The fact that globular clusters fit the extrapolation of the  $M_{\bullet} - \sigma$  and  $M_{\bullet}$ -luminosity correlations for massive black holes raises the possibility that there may be some previously unrecognized connection between the formation and evolution of galaxies, globular clusters and their central black holes.

Just as the correlation between the BH mass and bulge properties of the galaxies sheds light on their formation and evolution histories, the existence of BH in globular clusters may help in understanding the evolution of globular clusters, and how significantly, for instance, might the evolutionary effects influence the survival of a cluster with a central IMBH.

Fig. 3 shows  $R_h$ , the radius that contains half of the cluster stars in projection, plotted against  $M_V$ , the integrated luminosity, for 146 Galactic globular clusters, highlighting the separate sets of GCs by different symbols. The candidate set of Baumgardt et al. (2005) is denoted by green asterisks, the CC and post-CC candidates by red asterisks and the remaining Galactic clusters are marked by blue triangles. Most theories agree that present-day IMBHs most probably reside in massive, dense and concentrated globular clusters, for example, the ones that occupy the region near and under the straight line in Fig. 3, rather than in loose and dissolving clusters, i.e., clusters from the so-called ‘graveyard’ (Mackey & van den Bergh 2005) — the rightmost region in Fig. 3. There is a sharp edge to the main distribution of the clusters (the Shapley line, van den

Bergh 2008b), and only three Galactic clusters ( $\omega Cen$ , M54 and NGC 2419), and an M31 cluster G1 (marked by a black asterisk), lie above the upper envelope. All of these globular clusters, including the rather diffuse NGC 2419 (the uppermost left blue triangle), are believed to be the stripped cores of now-defunct dwarf spheroidals accreted by our Galaxy. Though the recent work by van den Bergh (2008a) indicates that this plot may be not the best way to distinguish between globular clusters and dwarf spheroidals, (for example, NGC 2419 may still be a genuine globular cluster, see refs in van den Bergh (2008a)), it confirms  $\omega Cen$ , M54 and G1(M31) to be ex-dwarfs on the basis of their ellipticity. Several clusters, *viz.*, 47 Tuc, M15, NGC 6388 and NGC 6441, which is one of the four brightest Galactic globular clusters, lie very close to this line. The clustering of our candidates in a central area of the plot, in the region where the clusters that are both ‘tight and bright’ lie, may indicate that dense and high-luminosity clusters are better candidates for central black hole searches than diffuse and low-luminosity ones.

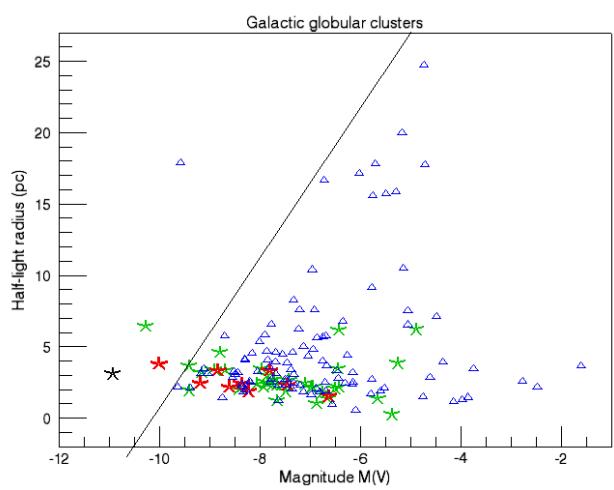


Fig. 3.—  $R_h$  vs  $M_V$  for 146 Galactic globular clusters (data from Mackey & van den Bergh (2005)). The Baumgardt’s set is marked by red asterisks; the CC set by green asterisks; the remaining clusters by blue triangles. The M31 globular cluster G1 is marked by a black asterisk, the measurement for its  $R_h$  is taken from Barmby et al. (2002). Above the slanted line the red asterisk marks  $\omega$  Cen, the green asterisk M54.

While some have argued on theoretical grounds that a central IMBH in the core may increase the stability of the cluster and thus its efficiency to withstand the tidal disruption for a longer time during its passages through the Galaxy (e.g., Hansen & Milosavljević 2003), the

contrary view also exists, that a central IMBH speeds up the dissolution of a star cluster, especially if a cluster is surrounded by a tidal field (Baumgardt et al. 2004). The observational consequences of the latter view are that there may exist a population of ‘rogue’ IMBHs in the Galaxy (as MACHOS, for example), and that if such a cluster spirals into the Galactic centre, the result would be an IMBH with a group of stars still tidally bound to it (for example, it can explain the existence of a stellar complex IRS 13E within 1 pc of the Galactic centre as the remains of a GC with an IMBH (Hansen & Milosavljević 2003)). However, isolated IMBHs as MACHOs would have been detected by microlensing surveys, which, incidentally, have ruled out the existence of MACHOs in the mass range of  $10^{-8} - 100 M_\odot$ , and recently, at the 95% confidence level, MACHOs with masses  $M > 43 M_\odot$  were excluded at the standard local halo density (Yoo et al. 2004), thus closing the MACHO mass window of  $30 - 10^3 M_\odot$ . The second suggestion that the Galactic central complex IRS 13E consists of an IMBH with few stars still bound to it has also been ruled out (Mužić et al. 2008).

Additional circumstantial evidence comes from the observations that clusters with high central concentration index ( $c = \log r_{\text{tidal}}/r_{\text{core}}$ ) appear to have retained their low-mass stars, when compared to low-concentration clusters that show serious depletion. A cluster loses low-mass stars due to evaporation, and mass segregation plays an important role in this process by pushing the low-mass stars to the periphery of the cluster. However, it is expected that IMBH in the globular cluster centre would quench mass segregation (Gill et al. 2008). The degree of mass segregation present was already applied to rule out the presence of an IMBH in a low-concentration, small Galactic globular cluster NGC 2298 (Pasquato et al. 2009), which is also heavily depleted in low-mass stars (De Marchi et al. 2007). Incidentally, NGC 2298 has a large core, which reinforces the conclusions of Hurley (2007) that a large core is not necessarily an indication of the presence of an IMBH in a globular cluster.

Thus, if the formation of a central black hole is a normal stage in the life of a globular cluster, current observations favour that its presence would aid the survival of the globular cluster in the field of the Galaxy.

#### 4.2 Model predictions; deviations from the log-linear relation

Though the GRG sample statistically favours a log-linear relation, Barth et al. (2005) noticed that it is possible that the low-mass AGN sample does flatten the  $M_\bullet - \sigma$  curve somewhat. They warn that while it

is still too early for any definitive conclusion, it may be that AGNs follow a different  $M_\bullet - \sigma$  relation altogether. However, the sample of Greene & Ho (2006) completely rules out the steepening of the slope (Barth et al. 2005). We have applied log-square and log-cubic fits to our full sample in addition to the log-linear fit, and have calculated the AIC and BIC factors for these fits (using R Project software (2007)).<sup>2</sup> Table 4 shows the values for these parameters. It can be seen from the Table that log-linear relation provides a better fit to the  $M_\bullet - \sigma$  relation for the full sample. It should also be noted that the possible (low-significance) log-quadratic fit to GRG sample, reported in Gültekin et al. (2009) and shown by a curved line in the left panel of Fig. 1, is ruled out once low-mass AGN and globular clusters are taken into account.

**Table 4**

Full sample	AIC	BIC
Log-linear*	83.857	90.37
Log-quadratic†	85.518	94.22
Log-cubic‡	85.747	96.62

\*  $y = \alpha + \beta x$ , see Eq. 1,

†  $y = \alpha + \beta_1 x + \beta_2 x^2$ ,

‡  $y = \alpha + \beta_1 x + \beta_2 x^2 + \beta_3 x^3$ .

The remarkable consistency of the  $M_\bullet - \sigma$  correlation can be used as a constraint on cosmological models making specific predictions for the low-mass end of the  $M_\bullet - \sigma$  relation. The low-mass cut-off in the BH mass function today provides a constraint on the mass function of seed black holes for the SMBH. If BH seeds are formed from the remnants of Population III stars and have masses of  $\sim 100 M_\odot$ , the so-called ‘light-seed model’, the merger tree calculations predict high BH occupation fractions in low-mass galaxies (Volonteri et al. 2008), though with such a steep slope of  $M_\bullet - \sigma$  relation that some galaxies hosting very tiny ( $< 10^4 M_\odot$ )

<sup>2</sup>The idea behind the Akaike Information Criterion (AIC, Akaike 1974) and Bayesian Information Criterion (BIC, Schwarz 1978) is that we expect the model with more parameters (e.g. log-quadratic) to achieve a higher maximized log-likelihood than the model with fewer parameters (log-linear model). However, it may be that the additional increase in the log-likelihood statistic, achieved with more parameters, is not worth adding the additional parameters. The smaller AIC values for the log-linear fit indicate that linear fit is better, that is worth the additional parameters. However, since AIC is known to tend to overfit sometimes, i.e., it may favour models with more parameters than they should have, we have also calculated the BIC criteria, which imposes a larger penalty for increase in the number of parameters than AIC.

black holes. The steepening of the  $M_\bullet - \sigma$  slope after  $\sigma \sim 150$  km/sec is also predicted in the hierarchical black hole growth scenario by Granato et al. (2004), where supernova feedback becomes more efficient at slowing the AGN fueling rate.

Another prediction, proposed by Wyithe (2006), was that this relation should flatten in the range between 70 to 380 km/sec, in other words, a log-quadratic relation providing a better fit to the sample of SMBH masses and velocity dispersions. One of their predictions was that in bulges with  $\sigma \sim 10$  km/sec the minimum mass of the black hole shall be  $\sim 10^5 M_\odot$ . The same flattening (at 20 – 50 km/sec) is predicted in the 'heavy-seed' model (Volonteri et al. 2008). The different 'seed' cases show markedly different behaviour for the predicted BH occupation fraction and  $M_\bullet - \sigma$  relation at low masses, thus making globular clusters an ideal laboratory to differentiate between the models.

## 5 Conclusions

We extend the  $M_\bullet - \sigma$  relationship for galaxies to lower black hole masses using black holes discovered in globular clusters. The reported masses of black holes in the centres of globular clusters M15, 47 Tuc,  $\omega$  Cen, NGC 6388 and G1 are consistent with the linear extrapolation of the  $M_\bullet - \sigma$  relationship for galaxies to the low-mass end. Using this extrapolated relationship, we have estimated the masses of putative black holes in a sample of globular clusters, and find that these clusters are consistent with the  $M_\bullet$ –luminosity relationship as well.

In the extended  $M_\bullet - \sigma$  plot, points corresponding to different types of stellar systems occupy distinct regions, suggesting that black hole masses of  $\sim$  few  $\times 10^4 M_\odot$  represent the *lowest* limit for the central black holes of galaxies. Masses of the central black holes that are below this limit correspond to the globular cluster domain (keeping in mind that G1 and  $\omega$  Cen are believed to be tidally stripped dwarf galaxies and not genuine globular clusters).

The consistency of black hole masses in globular clusters with the extrapolated  $M_\bullet - \sigma$  and  $M_\bullet$ –luminosity relationships reinforces the idea that globular clusters harbour IMBHs in their centres. The central black holes of globular clusters place even stronger constraints than low-luminosity AGNs on theoretical models of supermassive black hole growth and evolution. If black holes in globular clusters do exist, they will rule out models that predict either steepening or flattening of the  $M_\bullet - \sigma$  relation the low-mass region.

### A Appendix. Additional galaxies to the GRG sample.

**Table 5** Additional galaxies

Galaxy	Type	$M_\bullet$ (high,low) ( $10^6 M_\odot$ )	$\sigma_e$ (km/sec)	$M_V$	Method
NGC2974	E4,Sy2	170.0(190., 150.)	$236 \pm 12$	-21.09	s
NGC3414	S0	250.0(280., 220.)	$205 \pm 10$	-20.25	s
NGC4395	Sm, dwarf	0.36(0.47, 0.25)	$30 \pm 5$	-11.00	r
NGC4552	E,L	500.0(550., 450.)	$263 \pm 13$	-21.65	s
NGC4621	E5	400.0(440., 360.)	$231 \pm 12$	-21.74	s
NGC5813	E1,L	700.0(770., 730.)	$237 \pm 12$	-22.01	s
NGC5846	E0	1100.0(1200., 1000.)	$238 \pm 12$		s
NGC7332	S0	13.0(19.0, 8.0)	$125 \pm 16$	-19.62	s
IC2560	SBb,Sy2	2.9(3.5, 2.3)	$137 \pm 14$	-20.7	m
POX52	dE,N	0.14(0.25, 0.03)	$36 \pm 5$	-17.6	multiple

*Key to columns:* (1) name of the galaxy, (2) Hubble type of the galaxy and activity of the nucleus if present (Sy1 = type 1 Seyfert; Sy2 = type 2 Seyfert, L = LINER), (3) mass of the central black hole (high, low), (4) effective stellar velocity dispersion of the bulge, (5) absolute V-band luminosities are taken from Lauer et al. (2007) with the following exceptions: NGC 4395 (Peterson et al. 2005), IC2560 (Hunt 2004) and POX52 (Barth et al. 2004); (6) detection method (s = stars, g = gas, m = H<sub>2</sub>O masers, r = reverberation mapping).

### Appendix B. Candidate Globular Clusters.

**Table 6** Globular clusters with predicted masses for central black holes.

Cluster	Other	$M_\bullet(10^3 M_\odot)$	$\sigma(\text{km/sec})$	$M_V$	Reason	Other predictions ( $M_\odot$ )
NGC362		$73.9 \pm 10.2$	$6.2 \pm 3.0$ [1]	-8.41	c?	
NGC1851		$917.0 \pm 1.7$	$11.3 \pm 2.5$ [1]	-8.33	HVS	
NGC1904	M79	$35.3 \pm 3.1$	$5.2 \pm 1.04$ [3]	-7.86	c?	
NGC2808		$1874.7 \pm 2.8$	$13.4 \pm 2.68$ [2]	-9.39	HVS,radio,EHB	550[2],110-3100[3]
NGC5286		$291.6 \pm 10.9$	$8.6 \pm 4.3$ [1]	-8.61	B.	
NGC5694		$69.0 \pm 3.14$	$6.1 \pm 1.3$ [1]	-7.81	B.	
NGC5824 <sup>†</sup>		$850.8 \pm 2.3$	$11.1 \pm 1.6$ [1]	-8.84	c?,HVS,B.	
NGC5904	M5	$90.1 \pm 10.6$	$6.5 \pm 3.2$ [1]	-8.81	radio	320[2]
NGC6093	M80	$2610.4 \pm 9.7$	$14.5 \pm 7.0$ [1]	-8.23	HVS,EHB,B.	1600[1],1000-1200[3]
NGC6205	M13	$130.5 \pm 2.9$	$7.1 \pm 1.42$ [3]	-8.70	radio,EHB	250[2],130-2400[3]
NGC6256	Ter12	$96.1 \pm 12.0$	$6.6 \pm 3.4$ [1]	-6.52	c	
NGC6266	M62	$3360.7 \pm 9.6$	$15.4 \pm 7.4$ [1]	-9.19	c?,HVS,radio,EHB,B.	3000[1],450[2],290-1500[3]
NGC6273		$1335.8 \pm 2.0$	$12.36 \pm 1.24$ [6]	-9.18	radio	410[2]
NGC6284		$108.9 \pm 11.1$	$6.8 \pm 3.4$ [1]	-7.97	c	
NGC6293		$238.8 \pm 11.7$	$8.2 \pm 4.2$ [1]	-7.77	c	
NGC6325		$84.4 \pm 12.1$	$6.4 \pm 3.3$ [1]	-6.95	c	
NGC6333	M9	$172.7 \pm 2.2$	$7.59 \pm 0.76$ [6]	-7.94	c	
NGC6342		$35.3 \pm 11.22$	$5.2 \pm 2.6$ [1]	-6.44	c	
NGC6355		$356.2 \pm 2.1$	$9.02 \pm 0.902$ [6]	-8.08	c	
NGC6380	Ton1	$77.5 \pm 2.25$	$6.27 \pm 0.63$ [6]	-7.46	c?	
NGC6397 <sup>†</sup>		$19.3 \pm 2.38$	$4.5 \pm 0.45$ [6]	-6.63	c,B.,radio	390-1290[10]
NGC6402		$238.8 \pm 2.9$	$8.2 \pm 1.64$ [3]	-9.12	radio	390[2]
NGC6440		$352.9 \pm 3.1$	$9.0 \pm 2.0$ [7]	-8.75	radio	300[2]
NGC6441		$549.1 \pm 2.8$	$10.0 \pm 2.0$ [7]	-9.64	HVS,radio	470[2]
NGC6453		$114.3 \pm 2.2$	$6.88 \pm 0.68$ [6]	-6.88	c	
Ter 6	HP5	$131.3 \pm 2.2$	$7.11 \pm 0.7$ [6]	-7.67	c	
NGC6522		$146.6 \pm 9.9$	$7.3 \pm 3.5$ [1]	-7.67	c	
NGC6541 <sup>†</sup>		$238.8 \pm 3.6$	$8.2 \pm 2.1$ [2]	-8.37	c?,B.	
NGC6544		$364.6 \pm 2.1$	$9.07 \pm 0.91$ [6]	-6.66	c?	
NGC6558		$6.7 \pm 12.4$	$3.5 \pm 1.8$ [1]	-6.46	c	
NGC6624		$41.4 \pm 2.3$	$5.4 \pm 0.54$ [1]	-7.49	c	
NGC6626	M28	$242.5 \pm 2.5$	$8.23 \pm 1.28$ [2]	-8.18	radio	210[2]
NGC6642		$10.1 \pm 2.4$	$3.86 \pm 0.39$ [6]	-6.77	c?	
NGC6656	M22	$5075.5 \pm 1.9$	$16.99 \pm 1.7$ [5]	-8.50	radio	240[2]
NGC6681	M70	$549.1 \pm 3.56$	$10.0 \pm 2.6$ [1]	-7.11	c	
NGC6715	M54	$10491.2 \pm 1.64$	$20.2 \pm 0.7$ [8]	-10.01	HVS,radio,EHB,B.	960[2],700-3200[3],9400[9]
NGC6752		$1354.0 \pm 1.80$	$12.4 \pm 0.5$ [4]	-7.73	c,HVS,PSR	500-1000[4]
NGC7099	M30	$48.2 \pm 2.3$	$5.6 \pm 0.56$ [2]	-7.43	c	

*Key to columns:* (1)-(2) cluster identification number and other name, (3) calculated BH mass with error bars, (4) central velocity dispersion with reference; when the error on dispersion was not given, we assumed it at 10%, (5) V-band absolute magnitude, (6) references to the reasons of selection, (7) masses predicted in the literature.

<sup>†</sup> Not likely to host a black hole according to Baumgardt et al. (2005); belongs, however, to the “c” set.

*References to velocity dispersions:* (1) Dubath et al. (1997), (2) Pryor & Meylan (1993), (3) McLaughlin & van der Marel (2005), (4) Drukier et al. (2003) (5) Chen et al. (2004) (6) Webbink (1985), (7) Origlia et al. (2008); (8) Ibata et al. (2009)

*References to the reasons of selection:* “c”=post-core-collapse (pcc) morphology; “c?”=possible p.c.c. (Trager et al. 1995; Lgger et al. 1995); “HVS”=high velocity stars (Drukier & Bailyn 2003); “radio”=radio observations (Maccarone 2004; Bash et al. 2008); “EHB”=extreme horizontal branch stars (Micocchi 2007); “PSR”=detection by pulsar dynamics (Colpi et al. 2003); “B.”=Baumgardt’s sample (Baumgardt et al. 2005).

*References to other predictions:* [1] Bash et al. (2008): mass estimates from  $M_\bullet - \sigma$  relation; [2] Maccarone (2004): mass estimates from  $M_\bullet = 0.1M_{\text{cluster}}$ ; [3] Micocchi (2007): mass estimates from the observed standard concentration parameter and slope of the central surface-brightness profile; [4] Colpi et al. (2003): mass range inferred from dynamical estimates; [9] Ibata et al. (2009): this mass is the best fit from observations of velocity and density cusps; [10] de Rijcke et al. (2006): mass estimate from  $3\sigma$  upper limit on radio emission.

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